MODELING THE LIFE CYCLE COST OF JET ENGINE MAINTENANCE

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Abstract

The present paper originates from a student's thesis and discusses an approach for estimating the life cycle cost of aircraft engine maintenance. It provides resources on the primary factors that affect the maintenance cost of commercial aircraft engines. Building on these resources, it is shown how a parametric cost estimating model can be developed using available historic engine maintenance data. Such a model is capable of estimating the intervals of engine shop visits and the respective costs incurred at each shop visit. The primary influence factors of the model can be broken down to engine take-off thrust, engine dry weight, average flight length, applied derate and environmental conditions. The resulting model complements an aircraft life cycle cost simulation tool, which is being developed at the Institute of Air Transportation Systems at Hamburg University of Technology and DLR.

1. INTRODUCTION

The global market for passenger and freight air transportation has tremendously grown over the past decades and it is expected to keep expanding at a high pace. At the same time, the airlines see themselves in a more competitive market environment, especially with the emerging number of low-cost-carriers that has marked a turning point in the market structure. In order to stay competitive, airlines need to constantly seek cost saving potentials. This ambition is closely linked to evaluating new technologies and their possible contribution to reducing the long term costs for owning and operating the entire aircraft system throughout its life cycle. A considerable share of these life cycle costs (LCC) are expenditures for maintenance, repair and overhaul (MRO) of the individual aircraft systems. The biggest proportion of the aircraft MRO cost is incurred by the engine (see Figure 1).

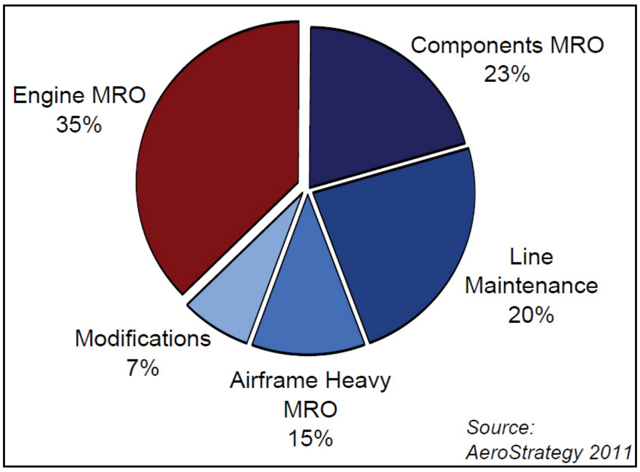

Figure 1 Aircraft MRO cost overview

The mechanical complexity of aircraft engines results in considerable labour cost required for MRO related tasks such as disassembly, inspection, reassembly and test. In addition, the engine design requires highly tensile and thermo resistant materials, which results in high material cost for repair and replacement of worn parts. Therefore, engine MRO is considered as cost driver and it is in the interest of aircraft operators to estimate the life cycle costs caused by engine maintenance, when making decisions regarding their engine fleet.

Traditionally, engine maintenance costs have been modeled as part of the aircraft direct operating costs (DOC). Various methods for the estimation of aircraft DOC exist. Many are derived from the ATA-67 DOC method [ATA67]. Two examples are the DOC methods described by Roskam [Ros90] and Scholz [Sch98] where the direct engine maintenance costs are considered to comprise a labour and a material cost component. However, these models are generally less suitable for a comprehensive life cycle consideration, as they lack the prediction of the point in time when the costs occur. In addition, these models have to be constantly updated to hold up to the technological development.

The assignment of the original thesis as basis for this paper is the development of an alternative method that is capable of predicting the MRO costs of commercial jet engines, using the method of parametric cost modeling based on recent historic data. The focus of the model is supposed to lie on the engine MRO that is performed in regular intervals off-wing in dedicated engine workshops. It should also enable the estimation of the interval length between engine overhauls, as this is relevant for a life cycle consideration. This work is intended to complement an existing method for considering the various maintenance events of an aircraft life cycle as part of a life cycle cost (LCC) simulation tool. The LCC-tool enables the evaluation of new technologies under the incorporation of expert's knowledge in form of technology factors. Therefore, the model is not aimed to forecast accurate figures of engine MRO costs and intervals. It rather intends to qualitatively reflect the general influence factors of engine maintenance and estimate reasonable cost and interval figures accordingly.

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2. JET ENGINE TECHNOLOGY

Today's commercial aircraft are equipped almost exclusively with gas turbine engines. The by far most common type of gas turbine engines in large commercial aircraft is the high-bypass turbofan. Therefore, the present study concentrates solely on this gas turbine type. The design of conventional turbofan engines is generally based on either a two-spool or three-spool configuration. In the more common two-spool turbofan, the low-pressure compressor (LPC) stages and the fan stages are mounted on one shaft together with the low-pressure turbine (LPT). The second shaft is hollow and carries the high-pressure compressor (HPC) as well as the high-pressure turbine (HPT). The three-spool concept includes an additional spool with intermediate compressor and turbine. This way, the fan and the first compressor stages can rotate independently at their optimum speed allowing higher compressor efficiencies. The disadvantage of the three-spool design is its relative complexity. Figure 2 displays the cross section of an example two-spool turbofan engine.

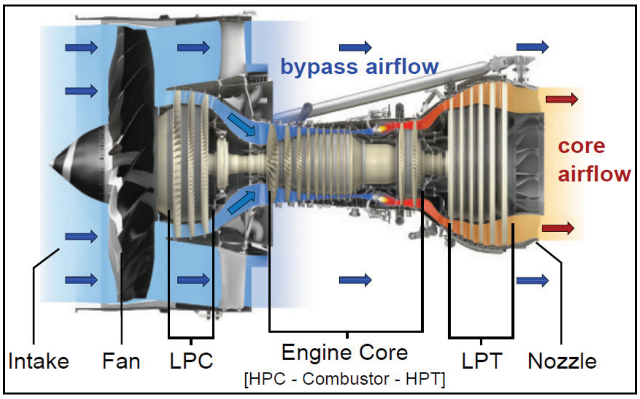

Figure 2 GEnx-2B - high bypass two-spool turbofan

2.1. Engine Module Layout

The design of today's turbofan engines follows a modular concept. This design essentially reflects in maintenance aspects. Each of the modules has its own identity, service history and specific inspection schedules. During a shop visit, any of the individual modules can be removed from the engine as an entire unit without disassembling it into its piece parts. The modular layout largely follows the arrangement and nomenclature displayed in Figure 2 with the addition of the accessory box, which is not illustrated. Hence, the main engine modules can be summarized as follows:

- Fan
- Low-Pressure Compressor (LPC)
- Core Engine Module
- Low-Pressure Turbine (LPT)
- Accessory Gearbox

Generally, it is the core engine module that is subjected to the most adverse conditions in terms of temperature, pressure and rotational velocity. It will be this module that suffers the fastest deterioration of performance. In addition to its main components the engine needs various systems to become operable. These include amongst others an air cooling and sealing system, a lubrication system, a fuel distribution system, an exhaust and thrust reverser system as well as an air inlet and a nozzle [Lin08].

2.2. Exhaust Gas Temperature Margin (EGTM)

Modern aircraft are equipped with a multitude of gauges to provide the flight crew with feedback information about the engine condition. The exhaust gas temperature (EGT) and the closely related EGT margin (EGTM) are the most important health monitoring parameters. The EGT is the temperature of the exhaust gases as they enter the tail pipe, after passing through the LPT. It is a measure of the engine's efficiency in producing its design level of thrust. A high EGT may indicate that the engine has suffered significant hardware deterioration during service. Generally, the EGT reaches its maximum during take-off or right after lift-off, as the engine operates at its peak then.

The EGT margin of an engine is the difference between the maximum tolerable EGT (Redline EGT) and the peak EGT during take-off. The redline EGT is the temperature limit, which cannot be exceeded without damaging the engine [Bra04]. As the EGT of an engine increases over time, due to hardware deterioration, the EGT margin decreases. Theoretically, engines can remain on wing until their EGT margin has become zero. The EGT margin is furthermore highly influenced by the present outside air temperature (OAT). For a given thrust setting, the EGT rises at a constant rate as the OAT increases. Figure 3 shows the relationship between take-off EGT and OAT. As the OAT rises, the air density decreases. Therefore, the throttle has to be increased in order to maintain constant thrust, which results in an increase in EGT. However, constant maximum thrust is only maintained up to a certain OAT (corner point). The engine power control is then programmed to keep the EGT constant for OATs higher than the corner point temperature. This power management setting is called flat rating and makes sure that the engine operates with enough EGT margin also at high OATs [Air06].

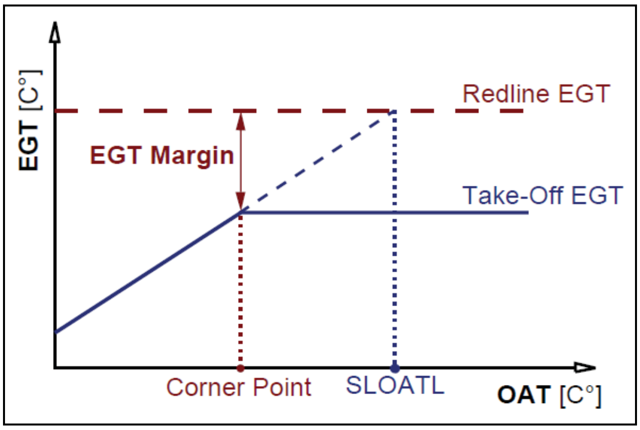

Figure 3 Correlation between EGT and OAT [Air06]

3. ENGINE MAINTENANCE

The aircraft engine as a major airplane component, in terms of investment, operating costs as well as its complexity, follows its own overhaul schedule mostly independent from the regular maintenance check events of the remainder aircraft. Modern engine maintenance is based on the so called on-condition method. Engine removals and overhauls only take place when the engine condition demands it [Rup00]. Similar to the maintenance of the remainder aircraft, engine maintenance can be divided into on-wing and off-wing maintenance, the latter is in the following referred to as shop visit (SV). On-wing maintenance is largely part of the aircraft line maintenance and has the objective to monitor the engine condition as well as extend its time on-wing (TOW). As such it is included in the maintenance planning document (MPD) of the aircraft. However, the present paper focuses on the estimation of the shop visit events, which is why on-wing maintenance is excluded from this study.

3.1. Main Effects on Engine Shop Visits

With regards to the implementation into a life cycle cost simulation tool, it is of interest to estimate the time when a shop visit becomes necessary as well as the costs incurred at each shop visit. These variables are strongly interrelated. It is obvious that an engine's shop visit gets more excessive the longer it is in operation. However, decisive for the operator are the maintenance cost per flight hour. In general, the objective is to keep the engine on-wing until a minimum of maintenance cost per flight hour is achieved [Eng10]. Various effects influence the engine's time on-wing as well as the costs incurred at shop visits. They are described in the following.

3.1.1 Operational Severity

The engine's time on-wing and thus the shop visit cost are heavily influenced by the engine's operating conditions. More demanding conditions will result in greater stress on the engine and therefore increase the wear of the engine hardware. Decisive measures for the operational severity include:

- Average flight time
- Take-off derate
- Outside air temperature
- Environment

During one flight cycle, it is the take-off and climb phase, where the engine is exposed to the greatest thermal stress and engine wear. Hence, the EGT margin of engines that are operated on short-haul routes will deteriorate relatively faster than those operating on middle or long-haul routes, as they are subjected to more take-offs during operation. The EGTM deterioration is additionally influenced by the applied take-off thrust level. The impact of both effects is often expressed through so called severity curves or matrices. These curves are dedicated to a particular engine variant and indicate a severity factor depending on the ratio between engine flight hour (EFH) and engine flight cycle (EFC) as well as the applied derate level. The severity factor is then used to adjust the maintenance cost per flight hour and the time on-wing of engines (Figure 4).

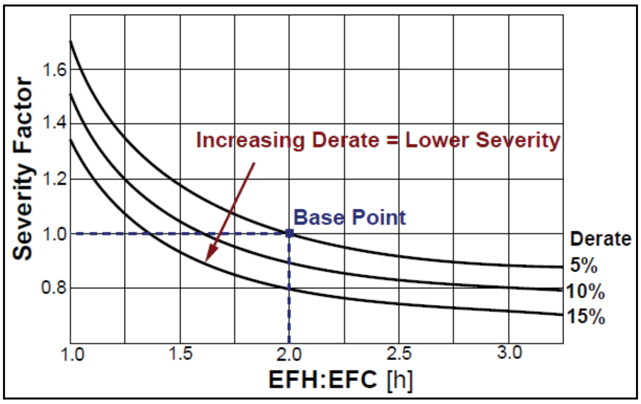

Figure 4 Example severity curve

As illustrated in Figure 3, the outside air temperature also directly influences the EGT margin and thus the hardware deterioration. In addition, one has to consider environmental conditions including particulate matter resulting from air pollution such as dust, sand, volcanic ash or industry emissions, which can increase the erosion of compressor and turbine blades. Furthermore, salty environments in coastal areas can accelerate the corrosion of engine components.

3.1.2 Engine Design

Naturally, the engine design has a considerable impact on the engine maintenance. In this study, three apsects regarding the engine design were identified:

- Thrust Rating
- Two-spool or Three-spool
- Target Application

Normally, there are several thrust ratings for a given engine model. The engine variants with higher thrust level generate higher gas path temperatures [Air05]. This results in a lower EGT margin and normally also in a more severe EGT and hardware deterioration, due to the increased thermal stress. In addition, it could be pointed out that engines with three-spool configuration generally achieve longer on-wing times but at the same cause higher total cost at shop visits. Eventually, engine maintenance characteristics were found to depend on the targeted application. Engines for short-haul aircraft (single aisle) of the Boeing 737 or Airbus 320 class have to be considered separately from wide body aircraft engines, which are designed primarily for middle and long-haul operation.

3.1.3 Engine Age

A general observation from analyzing engine maintenance data is that older, more used engines remain on-wing shorter and cost more to maintain than new engines. In terms of maintenance, an engine's life cycle can therefore be divided in first-run and mature-run phases. There is no clear definition when an engine's mature phase starts. Maturity may begin as early as after the first shop visit, depending on the engine model. In general, first-run engines will achieve considerably longer times on-wing than subsequent runs, as a result of increasing rates of hardware deterioration as the engine ages. However, once the engine reaches maturity, the shop visit intervals and cost stabilize to a relatively steady state [Ack10].

3.1.4 Shop Visit Management

Shop visit management is a broad field which includes many issues that directly or indirectly influence the shop visit cost and intervals. Hence, it is difficult to consider all effects in particular. For instance, there are different engine removal causes, such as EGT margin deterioration, expiry of life limited parts (LLP) or foreign object damage (FOD). The engine removal cause influences the necessary workscope of the shop visit and thus it's cost. In addition, there are different shop visit strategies which involve the management of the LLP lives as well as the extent of the workscope at each shop visit. This also includes decisions regarding the application of third party parts from manufacturers who hold the respective approval from the aviation authorities (PMA parts) as well as the repair strategy for components [Air99]. These considerations generally result from agreements between MRO provider and engine operator and can have a significant impact on the shop visit cost and intervals.

3.2. Shop Visit Cost

The proposed method is based on an alternative way of accounting for the direct engine maintenance costs (DMC) at shop visits if compared to the traditional DOC methods. In contrast to the common separation into material and labour cost, the total shop visit cost (SVC) can also be divided into **restoration** and **LLP** cost [Ack10]. In this case, restoration cost include for charges for labour and material related to restoring the engine's performance, while LLP cost reflect expenditures for the LLP replacement (see Figure 5).

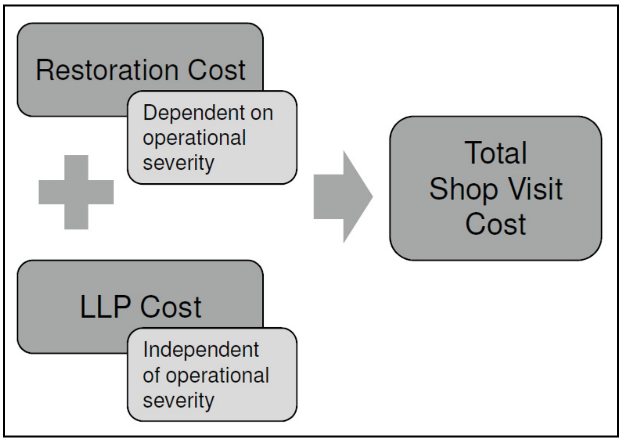

Figure 5 Shop visit cost composition

This cost breakdown allows to consider the significant impact of the operational conditions by adjusting maintenance costs via severity factors. It splits up the shop visit cost in one component that depends on the severity and one that is mainly independent from the operational conditions. Only the restoration cost are escalated according to the operational severity. The LLPs are independent, as they are replaced after a hard time regardless of the severity of the flight conditions. This hard time is usually expressed in engine flight cycles (EFC). In combination with the average shop visit interval length which is often expressed as shop visit rate, the total SVC can be expressed relative to the engine flight hours (EFH).

$$SVC = \ Cost \ incurred \ at \ shop \ visit \ \ [USD]$$

$$SVR = Shop \ visit \ rate \ \left[\frac{1}{EFH}\right]$$

$$SVC_{EFH} = SVC \ \ per \ \ flight \ hour \left[\frac{USD}{EFH}\right]$$

4. PARAMETRIC COST MODELING

Since the proposed method largely relies on the concept of parametric cost modeling, the development of cost estimating relationships (CER) based on historic data is a crucial step in the model development. The present study is based on the approach described in the NASA Cost Estimating Handbook [CEH08]. The applied iterative procedure can be divided into three parts:

1) Database Assembly
2) Data Analysis
3) Derivation of Prediction Functions

The objective is to find parametric relationships between engine specfications (e.g. dry weight, take-off thrust or bypass ratio) and the resulting shop visit cost throughout the engine's life cycle. In addition, it is required to predict the shop visit intervals.

4.1. Database Assembly

The assembly of an adequate database is critical for the success in developing CERs. Therefore, considerable effort is put time in reviewing different data sources as well as collecting and processing the available data.

4.1.1 Review of Data Sources

The actual data collection is preceded by an extensive review on the different available data sources. Here, the findings of the literature review regarding general engine maintenance characteristics (see Section 3), are incorporated in order to evaluate available data sources.

Standard technical specifications of aircraft engines, like take-off thrust and dry weight, are generally no sensitive data. Hence, they can be obtained directly from the engine OEMs (e.g. from company websites or other specification sheets). This is a primary source and it can be considered as reliable.
In contrast to technical engine data, cost and removal interval information are highly sensitive and well protected by the MRO providers and airlines. Hence, it is not possible to access primary sources. However, there is a range of secondary data sources that are available in the framework of this study. These include:

- Form 41 databases from the US Department of Transportation[3]
- MRO Prospector by the aviation magazine Aviation Week[4]
- Owner's & Operator's Guides of the aviation magazine Aircraft Commerce[5]
- AeroStrategy forecasts[6]

The Aircraft Commerce guides prove to be the most suitable source. This is because they provide maintenance data of a wide range of different engine models and variants, while giving the shop visit cost per flight hour divided in LLP and restoration cost (LLP cost are generally given in [USD/EFC]). They additionally indicate the operational severity of the shop visit estimates. However, it has to be noted that these articles are a secondary source based on the investigation results of the aircraft commerce editors.

4.1.2 Data Collection

The data is collected via searching the Owner's & Operator's Guides of numerous Aircraft Commerce issues for maintenance data of the currently mature engine generation. All collected data comes from estimates regarding mature engine models in the time from 2003 to 2010. For each reported engine variant the respective shop visit intervals and cost are extracted and saved in a excel table. In order to account for the aging effect, the shop visit data is collected separately for first and mature shop visits. The respective engine specifications are added using the engine fact sheets from the manufacturers. In addition, the engines are grouped into short-haul (SH) engines and medium-long-haul (MLH) engines, as they feature generally different maintenance characteristics. All together the final database contains about 75 entries.

4.1.3 Data Normalization

When considering the collected raw data, several notable inconsistencies arise. Firstly, the reviewed articles were issued over a time period of 8 years. Therefore, the cost

[3] http://www.bts.gov/data_and_statistics
[4] http://mrop.aviationweek.com/
[5] http://www.aircraft-commerce.com/
[6] http://www.aerostrategy.com/

figures have to be normalized for inflation in order to account for fluctuating cost for labour and material. This is done as suggested by Ackert [Ack10] using economic indices for labour and industrial commodities provided by the US Bureau of Labor Statistics[7].

Another critical issue is the average flight time of the shop visit estimates from the Aircraft Commerce articles. As discussed in 3.1.1, both the shop visit cost and the shop visit rate are significantly influenced by the average flight time. This effect cannot be modelled directly through the available data, it needs to be normalized before in terms of average flight times. The collected raw data contains the average flight time for all cost and interval estimates. The approach is to normalize this data to a standard flight time level. Theoretically, this is possible if for each engine of the database the corresponding severity curve was available (see Figure 4). In this case, a base flight time could be predefined and the severity factor that adjusts the cost and interval data to the level of the base flight time could be calculated for all data points. Each engine model and even each engine variant has a distinct severity curve. These curves are sensitive information that cannot be obtained from the engine manufacturers. However, it is possible to obtain example curves for a short-haul operating engines as well as for a medium-long-haul aircraft engines. Together with the scattered information on severity factors from the Aircraft Commerce articles, averaged severity curves are assembled for both SH-engines and for MLH-engines based on the example curves. The assumption is made that the entire range of distinct short-haul as well as medium-long-haul engines can be adequately adjusted using one averaged severity curve for each category.

4.2. Data Analysis

With the database assembled, the next step is the data analysis with the objective of identifying adequate cost estimating relationships. The data analysis process can be divided into screening for candidate relationships and subsequent regression analysis of the found relationships. Both stages are aided by the extensive use of statistical computer software[8]. The basic dependent variables to be modeled by CERs are the **shop visit intervals** and **shop visit cost per EFH,** while the costs are subdivided in restoration and LLP cost. Considering the separation of the collected data into first and mature engine shop visits, a total of six CERs appears to be necessary. However, during the data collection it has been established that the LLP cost of first and mature removals barely vary, which is why only one single LLP cost variable is further pursued. In this context it has to be noted that this consideration completely neglects the impact of LLP management on the actual cost at each shop visit. Instead LLP costs are understood as constant cost reserves. With the help of the statistical computer software it is attempted to establish CERs for each of the following dependent variables:

- First SV interval length
- Mature SV interval length
- First SV restoration cost
- Mature SV restoration cost
- LLP cost

In the process of the data analysis each of these dependent variables is screened for suitable relationships with the engine specifications of the database as independent variables. Each appropriate relationship is subsequently evaluated using the method of linear regression based on the best least square fit.

The result of this procedure is, that statistically only the engine dry weight, the take-off thrust as well as the ratio between these two specifications play a significant role in modeling the dependent variables. The interval analysis turns out to be more complicated. It is not possible to find acceptable regression results for the entire engine range in the database. This is a result of the different maintenance characteristics of short-haul and medium-long-haul engines. Analyzing the data separately for SH and MLH engines leads to acceptable regression results. As a consequence, the number of dependent variables is increased from five to seven, as two additional interval variables are added. It is noteworthy that the shop visit intervals of 3-spool engines cannot be adequately modeled together with the majority of two-spool engines, as they consistently show considerably longer intervals. Hence, they are excluded from the interval analysis. Figure 6 exemplarily illustrates the linear regression results for the LLP cost variable.

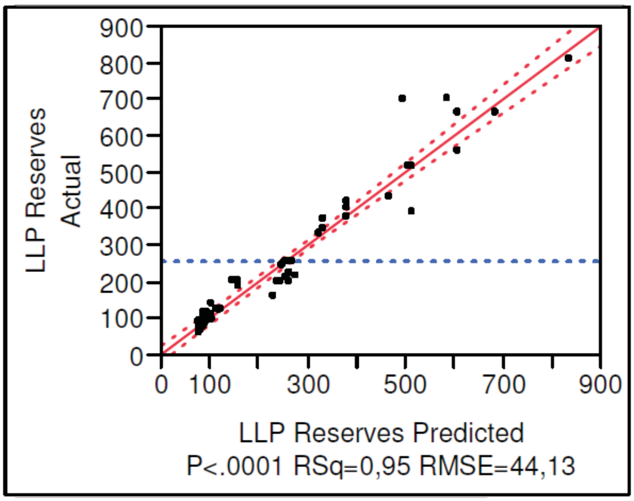

Figure 6 Regression analysis using JMP 8.0

4.3. Derivation of Prediction Functions

The data analysis results in seven cost estimating relationships each reflecting one of the targeted dependent variables. Only the three independent variables dry weight, take-off thrust and the ratio of both are found to be useful modeling parameters. The thrust-weight-ratio is denoted as TWR in the following. The found CERs are the basis for the derivation of the final prediction functions to be implemented in the cost estimating model. In order to reduce the complexity of the final model, the number of function terms is limited to three. The shape of the eventually established seven prediction functions differs in part significantly. They are summarized as follows, where first-run shop visits are denoted with FR and mature-run shop visits with MR.

4.3.1. Interval Prediction Functions

Intervals are given in engine flight hours (EFH) and the prediction functions are divided after short-haul (SH) and medium-long-haul engines.

Short-haul engines

$$\text{Interval}_{FR,SH} = 68466 - 8267.82 \cdot TWR - 1.004 \cdot \text{weight} + (\text{weight} - 5407) \cdot [(\text{weight} - 5407) \cdot 0.000121]$$

$$\text{Interval}_{MR,SH} = 40684 - 5022.8116 \cdot TWR$$

[7] http://data.bls.gov/cgi-bin/srgate

[8] JMP 8.0 from SAS

Medium-long-haul engines

$$\text{Interval}_{\text{FR,MLH}} = 22539 + 1.433 \cdot \text{weight} - 0.315 \cdot \text{thrust}$$
$$+ (\text{thrust} - 76305) \cdot [(\text{thrust} - 76305) \cdot 0.00000344\ ]$$

$$\text{Interval}_{\text{MR,MLH}} = 34415 - 2759.25 \cdot \text{TWR} - 0.3663 \cdot \text{weight}$$
$$+ (\text{weight} - 12072) \cdot [(\text{weight} - 12072) \cdot 0.00010179\ 5\,]$$

4.3.2. Cost Prediction Functions

The restorations costs are given in USD/EFH, while the constant LLP cost figure is given in USD/EFC.

Restoration Costs

$$\text{SV RC}_{\text{FR,EFH}} = 7 + 0.00236189 \cdot \text{thrust}$$
$$\text{SV RC}_{\text{MR,EFH}} = 46 + 0.00288612 \cdot \text{thrust}$$

LLP Cost

$$LLPCost = -115 + 0.01945 \cdot \text{weight} + 0.003121 \cdot \text{thrust}$$
$$+ (\text{weight} - 8608.781) \cdot [(\text{weight} - 8608.781) \cdot 2.69 \cdot 10^{-6}]$$

5. MODEL DEVELOPMENT

The assembled database and the resulting prediction functions predetermine parts of the model structure. However, since the established CERs are based on a normalized and reduced database, they do not reflect the impact of major factors such as flight time, derate, number of spools or flight environment. These effects have to be modeled separately.

5.1. Model Structure

The objective of the engine maintenance model is the estimation of shop visit intervals and cost. Since the established CERs distinguish between first-run and mature-run shop visits, there are four output parameters: SV interval and SV cost for each engine phase. The input parameters depend first of all on the necessary input for the derived prediction functions. These parameters are the engine's take-off thrust and its dry weight. Since the interval CERs are further divided in short-haul and medium-long-haul engines, an additional input parameter that determines what CER is applied, has to be introduced. This additional parameter was termed engine application and is considered as an engine specification, since it is a static parameter linked to the engine variant. All of these input parameters can be derived from the established CERs. However, as mentioned before, there are important effects that are not modeled in the CERs. Therefore, there are more input parameters necessary. These include the number of engine spools as well as operational factors like flight time, derate and information about the severity of the environment. Figure 7 illustrates the maintenance model as black box with a summary of all input and output parameters.

In order to match the two different output parameter types, the inner model structure contains two parallel computation lines (cost and interval line). Since the derived prediction functions do not model the operational severity and the engine spool design, these effects have to be modeled in conjunction with the normalized values from the prediction functions.

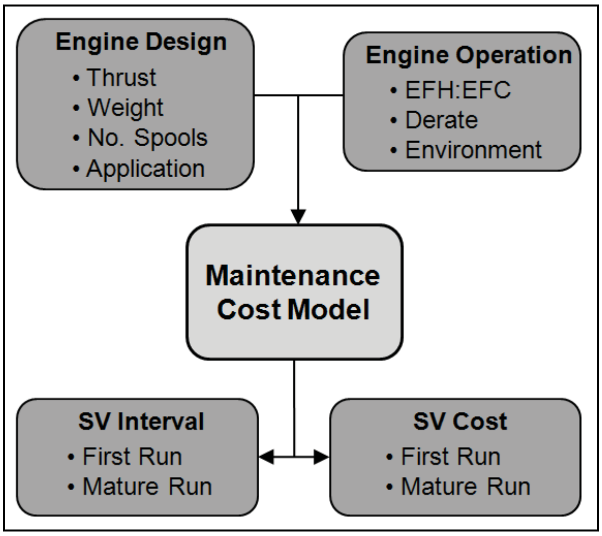

Figure 7 Input and output Parameter of the Model

Therefore, the inner structure of the model has been split into two serial modules. The first module reflects the established CERs through prediction functions, while the second represents all additional effects influencing the shop visit cost and intervals. The two modules are thus termed as follows:

- CER module
- Effect modue

The CER-module determines normalized base values for the shop visit cost and intervals. These base values are then adjusted in the effect-module with a series of adjustment factors. The adjustment factors are determined in correspondence to the respective input parameters. The entire inner model structure is illustrated in Figure 8. Both modules are described in more detail in the following.

5.2. CER-module

The CER-module basically consists of the seven prediction functions derived from the established cost estimating relationships (see rectangular frames in Figure 8). With the input of the engine weight and thrust plus the information if it is a SH or MLH engine, the CER-module generates five intermediate outputs:

- LLP Cost [USD/EFC]
- FR Restoration Cost [USD/EFH]
- MR Restoration Cost [USD/EFH]
- FR Base Interval [EFH]
- MR Base Interval [EFH]

These base outputs are valid only for the normalized conditions which the CER development was based on. The adjustment to the operational severity is performed in the following effect-module.

5.3. Effect-module

The effect-module, generates the factors necessary to adjust the base costs and intervals from the CERs according to the input of the operational severity and the number of engine spools. There are five factors (pentagon frames in Figure 8), which are subsequently described.The output of the Effect-Module are adjusted SV intervals and SVC per EFH divided in first-run and mature-run shop visits. The effect-module merges the LLP cost and the restoration cost from the CER-Module. Thus, it generates only four output parameters:

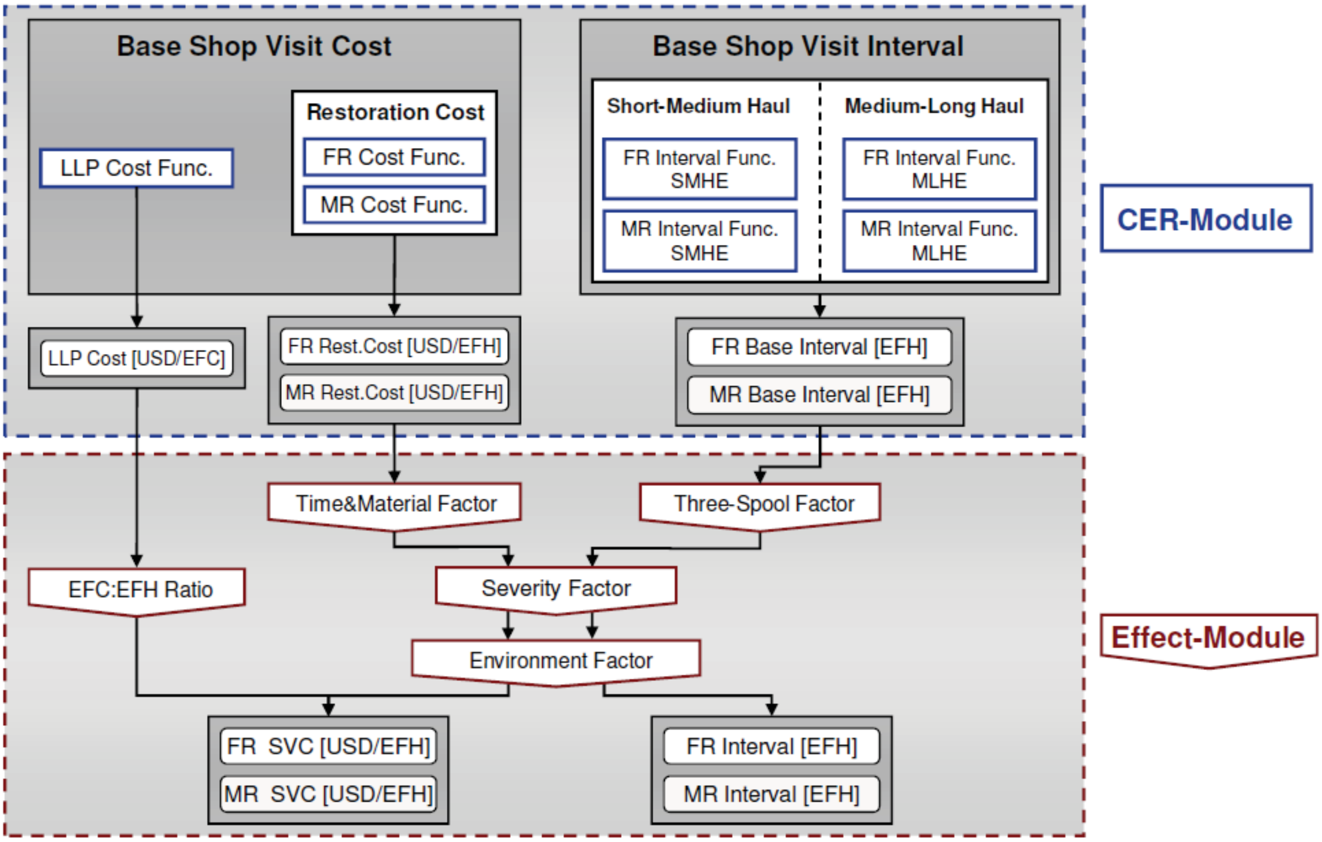

Figure 8 Inner structure of the developed cost estimating model

- FR Shop Visit Cost [USD/EFH]
- MR Shop Visit Cost [USD/EFH]
- FR Shop Visit Interval [EFH]
- MR Shop Visit Interval [EFH]

With this output, the absolute shop visit cost can be calculated through multiplying the SVC per EFH with the respective SV interval length.

5.3.1. Severity Factor

The severity factor (SF) adjusts restoration cost per flight hour and shop visit intervals in correspondence to the average flight time and derate under which the engine is operated. Since it is not possible to obtain the respective severity curve for each engine in the database, two average severity curves that approximate the impact of the operational severity for a range of engines are developed. These average curves are applied to normalize the flight time of the engines in the database and they are also the basis for modeling the effects of flight time and derate on the restoration cost and shop visit intervals as part of the effect-module. With the flight time and the derate as input, the severity curve gives out the corresponding severity factor which is then used to adjust the restoration cost and the interval by multiplication or division respectively. An excerpt of the applied severity curves is subsequently displayed for SH and MLH engines in shape of a matrix.

Table 1 Severity matrix for SH engines

EFH:EFC \ Derate	0%	5%	10%	15%	20%
0.5	2.800	2.600	2.400	2.280	2.160
1.0	2.100	1.925	1.750	1.645	1.540
1.5	1.600	1.450	1.300	1.210	1.120
1.9	1.240	1.120	1.000	0.940	0.880
2.5	1.000	0.910	0.860	0.792	0.744
3.0	0.920	0.840	0.780	0.738	0.696
4.0	0.826	0.766	0.706	0.670	0.634

Table 2 Severity matrix for MLH engines

EFH:EFC \ Derate	0%	5%	10%	15%	20%
1.0	2.800	2.500	2.200	2.020	1.900
2.0	2.000	1.850	1.700	1.610	1.520
3.0	1.600	1.500	1.400	1.340	1.280
4.0	1.405	1.315	1.225	1.171	1.117
6.0	1.140	1.070	1.000	0.958	0.916
8.0	0.990	0.935	0.880	0.847	0.814
12.0	0.890	0.845	0.800	0.773	0.746

5.3.2. Time & Material Factor

The time & material factor (TMF) is introduced to account for the effect that the absolute shop visit restoration cost (SVRC) generally increase with increasing time on-wing (TOW). When applying the same severity factor on the restoration cost per flight hour and the interval, the absolute SVRC remain constant regardless of the flight time or derate. However, the increased TOW due to raised derate and flight time should result in increasing SVRC. The time & material factor models this effect. Therefore, one could expect that the TMF can be expressed similar to the severity factor via multiple curves, only inverted so that the factor increases with decreasing flight time and derate. Analogue to the severity curves, averaged time & material curves for both SH and MLH engines were derived from the limited available data. However, due to the lack of data, these curves only take into account the effect of the flight time, which is why both developed curves were established as single curve (see Table 3 and Table 4).

Table 3 SH-engine, time&material curve data points

EFH:EFC	0.5	1.0	1.5	1.9	2.5	3.0	4.0
TMF	0.90	0.95	0.98	1.0	1.02	1.03	1.04

Table 4 MLH-engine time&material curve data points

EFH:EFC	1.0	2.0	3.0	4.0	6.0	8.0	12.0
TMF	0.85	0.91	0.94	0.96	1.00	1.05	1.11

5.3.3. Three-Spool Factor

The three-spool factor (TSF) models the effect of longer shop visit intervals for engines with a three-spool configuration compared to the more common two-spool engines. In general, there is no detailed additional information on the impact of the three-spool configuration on the achievable SV intervals accessible. However, since the database indicates that three-spool engines achieve significantly longer SV intervals, the available data is utilized to determine a simple constant factor that models this effect. This factor is determined through averaging the offset of the original three-spool data points over the generated intervals from the prediction functions of the CER-module with the respective three-spool engine specifications as input. However, it has to be noted that all three-spool engines of the database are MLH engines. It is assumed that SH engine are influenced in a similar manner. With the available data a three spool factor of TSF = 1.4 is established.

5.3.4. Environment Factor

The environment factor (EF) reflects the impact of the present environmental conditions including the outside air temperature on engine maintenance. Literature indicates that the flight environment influences the SV intervals and cost considerably. However, it was difficult to locate clear data on this topic. A possible consideration of the present environment was found in [Ack10]. Here, three levels of environmental severity are defined and related to a certain escalation factor. These environment levels and their correlating EFs are listed in Table 2. The respective EF is then multiplied with the overall SVR and SVRC in order to adjust the intervals and cost to the present environmental severity.

Table 5 Defined Environment Factors

Environment	EF	Typical Regions
Temperate	1.0	North America, Europe, Australia
Hot/Dry	1.1	Middle East, North Africa
Erosive	1.1	Coastal China, SE Asia, India

5.3.5. EFC:EFH Ratio

Strictly speaking, the EFC:EFH ratio is not a factor that is intended to model a certain influential effect on engine maintenance. Since the LLP cost are generally expressed in cost per engine flight cycle (USD/EFC), they have to be translated into cost per engine flight hour (USD/EFH) in order to be merged with the restoration cost. This is done by the EFC:EFH ratio, as the reciprocal value of the average flight time.

6. MODEL TESTING

The final model was eventually tested for its plausibility as well as sensitivity to the various input parameters, in order to evaluate the proposed approach.

6.1. Model Plausibility

The plausibility of the model is continuously monitored while developing the CERs and creating the model structure. These intermediate plausibility tests are backed by continuous correspondence with professionals in the MRO industry and significantly contribute to the decisions made throughout the development process. However, the final model is tested for its credibility in a more structured way. In general, it is important to avoid using the same data that was applied to develop the model for subsequent plausibility tests. It can be expected that the model reflects the collected data of the database. However, since the database is normalized and the final model structure includes not only the derived prediction functions but also a series of adjustment factors, it is first analyzed how well the final model reflects the original data points, prior to the flight time normalization. This is done by plotting the model results over the originally collected data and performing a linear regression analysis similar to the parametric cost modeling procedure.

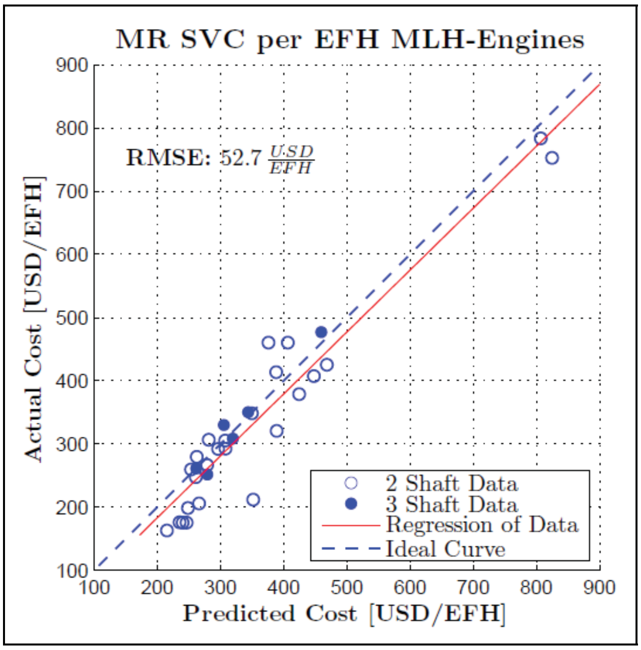

Figure 9 Model results versus original data points

Such a plot is exemplarily displayed in Figure 9 for the mature restoration cost of MLH engines. Here, the root mean square error (RMSE) refers to the error between the data points and the ideal blue dotted line, while the red continuous line represents the regression curve of the plotted data. In general, it can be established that the developed model is capable of reflecting the original data points very well with the normalization and the introduction of the effect-module. However, it has to be noted that there is only little data available for several possible operation scenarios, such as a MLH engine operated on short haul routes. Additional data would be necessary to back the model behavior in these regions. (see the two isolated data points in Figure 9)

In a second plausibility test, the model is compared with an additional independent data source. From the reviewed data sources, the AeroStrategy forecasts are selected as the only additional source that provides an adequate reference for a plausibility test. Unlike the remaining sources, the AeroStrategy predictions are characterized by a distinction of the different engine model variants and their application. Despite this, several assumptions have to be made in order to establish all necessary input parameters. This particularly includes the definition of an average flight time for each data point, as this is not specifically indicated within the data. In addition, it has to be noted that the AeroStrategy forecasts do not include the cost for LLP replacement. The plausibility is tested using the linear regression analysis as seen in Figure 9.
The outcome of this test is that the model qualitatively reflects the general trend of the AeroStrategy forecasts in terms of both intervals and cost. In addition, the predicted absolute values lie in the same dimension. It becomes apparent that the model tends to predict shorter intervals

and higher cost for the newest engine generation. This conclusion confirms the general observation that the technological advance results in extended times on-wing and lower maintenance cost, which is also reflected in the assembled database.

6.2. Model Sensitivity

Lastly, an extensive sensitivity analysis is performed in order to evaluate the effect of each input parameter on the different model outputs. Not all prediction functions are based on simple linear CERs. Hence, it is of interest to see how the shop visit cost and intervals react to changes of the input parameters. The results of this first sensitivity test largely reflect the expectations established as part of the literature review. However, there is no clear reference on the sensitivity of the shop visit cost and intervals to the defined model input parameters. Hence, further investigation has to be performed in order to validate the established model behavior.

Since the developed model is intended as part of a life cycle cost estimation model, the sensitivity of the total shop visit cost during an engine's life cycle to the different input parameters is also analyzed. Figure 10 displays a tornado chart which illustrates the impact of a 10% deviation of each input parameter on the shop visit LCC of SH-engines. The model indicates that it is especially the average flight time, the thrust and the environmental conditions, which largely define the total shop visit cost. MLH-engines are characterized by a similar relationship although the relative impact of the flight time is significantly smaller. The performed literature review supports this behavior of the model.

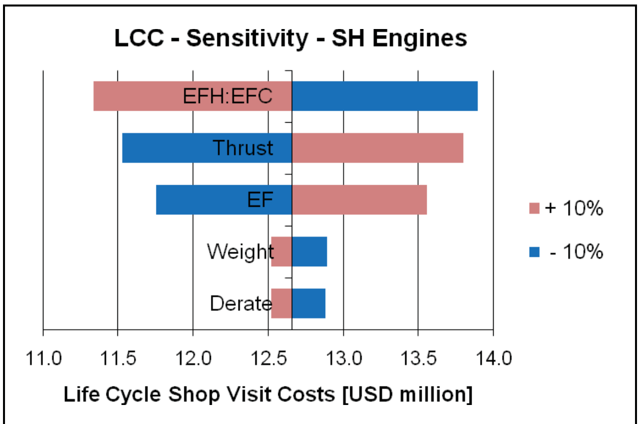

Figure 10 Sensitivity of life cycle cost for SH-engine

7. SUMMARY AND CONCLUSION

The present study demonstrates that openly available historic maintenance cost and interval data can be utilized to establish parametric cost estimating relationships (CERs) as basis for a prediction model of the life cycle cost of engine maintenance. In order to achieve this, a database that contains numerous current engine model variants and their shop visit intervals and cost was assembled from an extensive review of the operator & owner guides of the Aircraft Commerce magazine archive. Since, the data was not sufficient to reflect important effects like the operational severity and the number of spools, these effects had to be normalized for the database assembly. This led to CERs that do not reflect the influence of these factors. Therefore, the developed CERs were complemented by a subsequent effect-module that adjusts the results of the derived prediction functions according to the severity of the engine's operation and the engine design. The final model relates to six different input parameters: engine thrust, dry weight, number of spools, average flight length, applied derate and the present environment. Since the literature review and the assembled database indicated that short-haul operated engines generally exhibit different maintenance characteristics than engines that are operated on medium-long-haul routes, the model was split into two separate paths, each dedicated to one of these engine applications. In addition the model distinguishes between first-run and mature-run shop visits to account for the generally longer intervals and lower maintenance cost per EFH of new engines compared to engines that reached maturity.

The resulting model was tested for its plausibility by comparing the model results with available cost and interval estimations from AeroStrategy forecasts. The conclusion of these plausibility tests were that the general trend of the developed model and the Aerostrategy estimations coincide. However, the AeroStrategy forecasts for new generation tend to predict favorable intervals and cost if compared to the model results. This is not entirely unexpected, since the past has shown that newer generation engines generally achieve longer intervals and lower maintenance cost per EFH than the previous generation. Since the database assembly was limited to engines that have been in operation for the last two decades, the developed model reflects the current generation engines best. The problem is that there is no reliable data on the average intervals and cost for the newest engine generation. However, it can be assumed that the basic engine maintenance characteristics remain constant also with newer engine generations. Therefore, the derived prediction functions and adjustment parameters could be replaced with newly developed relationships that are based on prospectively available data for newer generation engines, while the rest of the model structure could remain unchanged. Alternatively, new maintenance data could be analyzed in an attempt to derive technology factors that could adjust the model results according to the advancements in engine technology.

Lastly the developed model was successfully implemented into the LCC simulation tool as an independent module. In addition several new functions were added. This most notably includes a flexible number of shop visits during an engine's life cycle depending on the defined yearly utilization. In addition, the model allows the consideration of charges for spare engines for the shop visit duration based on average engine leasing rates.

APPENDIX

Table 6 Table of considered engine models and variants

CFM56-3B1	CFM56-7B26	CF6-80C2A2	PW4052
CFM56-3B2	CFM56-7B27	CF6-80C2A3	PW4056
CFM56-3C1	CF34-3B1	CF6-80C2A5	PW4060
CFM56-5A1	CF34-8E5	CF6-80C2B6	PW4062
CFM56-5A5	CF34-8E5A1	CF6-80C2B1F	PW4158
CFM56-5B3	CF34-10E5	CF6-80C2D1F	PW4168
CFM56-5B5	CF34-10E6	CF6-80E1A2	PW4074
CFM56-5B6	CF34-10E7	GE90-85B	PW4077
CFM56-5B7	V2522-A5	GE90-110B	PW4090
CFM56-7B18	V2524-A5	RB.211-535E4	PW4098
CFM56-7B20	V2527-A5	Trent 772-60	PW2037
CFM56-7B22	V2530-A5	Trent 884-17	PW2040
CFM56-7B24	V2533-A5	Trent 895-17	

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